METHOD AND APPARATUS FOR ACOUSTIC DETECTION AND LOCATION OF DEFECTS IN STRUCTURES OR ICE ON STRUCTURES

CROSS-REFERENCE TO RELATED APPLICATION

This Application claims the benefit of provisional application No. 60/073,567, filed Feb. 3, 1998.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a method and apparatus for acoustic detection and location of defects in structures and/or ice on structures, and more particularly, to the non-destructive acoustic testing and evaluation of materials and mechanical structures utilizing an ultrasonic probing signal and low frequency vibration signal to identify and locate ice or integrity-reducing flaws such as cracks, fractures, delamination, unbonding, etc.

2. Related Art

Conventional active acoustic methods of ice detection and of non-destructive testing (NDT) are based on the principles of linear acoustics. These include effects of reflection, scattering, transmission, and absorption of probe acoustic energy. The presence of ice or a defect leads to phase and/or amplitude variation of received signals while the frequencies of the received signals are the same as the emitted probe signals.

The principal difference between the modulation technique of the present invention and linear acoustic NDT techniques is that the modulation technique correlates the presence and characteristics of a defect or of a material such as ice, with acoustic signals whose frequencies differ from the frequencies of the emitted probe signals. These signals with different frequencies are an outcome of a modulation transformation of the probe acoustic energy by a defect.

The modulation NDT methods have a number of advantages as compared with the linear acoustic techniques. Among them are high sensitivity and applicability to highly non-homogeneous and/or geometrically complex structures, such as composites, engine components, etc.

Previous efforts at NDT techniques include:

Perchersky, U.S. Pat. No. 5,520,052, discloses a method and apparatus for determining material structural integrity by combining laser vibrometry with damping analysis techniques to determine the damping loss factor of a material. The method comprises the steps of vibrating an area to be tested over a known frequency range and measuring vibrational force and velocity as a function of time over the known frequency range. Using known vibrational analysis, a plot of the drive point mobility of the material over the pre-selected frequency range is generated from the vibrational force and velocity measurements. Once computed, the damping loss factor can be compared with a reference stamping loss factor to evaluate the structural integrity of the material.

Larsen, U.S. Pat. No. 5,170,666 discloses a nondestructive evaluation of composite materials using acoustic emissions stimulated by absorbed microwave/radiofrequency energy. A specimen is exposed to pulsed radio frequency energy to produce an elastic wave that propagates on the surface of the specimen. The wave is detected by a piezoelectric or electro-optic displacement mode transducer which produces a signal corresponding to the wave. The signal is analyzed by a processor and classified.

Tsuboi, U.S. Pat. No. 5,214,960 discloses a method and apparatus for detecting defects in an object by vibrating the object in a plurality of positions. While the test object is vibrating, signals indicative of the vibration of the test object are detected and a signal indicative of a natural vibration of the test object is produced, and a signal indicative of a defect-induced vibration of the test object is produced. The signal indicative of the natural vibration and the signal indicative of the defect-induced vibration are compared to determine whether there is a defect in the test object.

Wajid, et al., U.S. Pat. No. 5,528,924 discloses an acoustic tool for analysis of a gaseous substance, specifically a refrigerant gas, to determine whether the sample contains significant contaminants. The refrigerant is tested by introducing a vapor sample into a resonant chamber which is formed to produced two distinct resonances, the resonator having first and second necks connecting first and second volumes. A frequency generator produces a sweep of frequencies in a band and then includes the two resonances and the sweep is applied to a transducer in one of the volumes. Another transducer responsive to vibrations produces an output signal that varies in response to the amplitude of the vibrations in the chamber. A digital circuit responsive to the frequency generator and the second transducer output determines the center frequencies for the first and second resonances and determines the frequency width of these resonances to determine quality or sharpness factors for the two resonances. Then the center frequencies and sharpness factors are compared with storage data and a determination as to the nature and extent of contaminants is made.

Rhodes, et al., U.S. Pat. No. 5,425,272 discloses the use of relative resonant frequency shifts to detect cracks. At least two prominent resonant frequencies of an object are sensed and the frequency difference is measured. The ratio of the frequency difference to one of the prominent resonant frequencies is determined and compared to predetermined criteria. Resonant frequency dependent upon dimensions will shift very little while resonant frequency dependent upon stiffness will shift a relatively large amount when an object has a crack.

Dixon, et al., U.S. Pat. No. 5,355,731 discloses a method for grading production quantities of spherical objects. A resonant ultrasound spectroscopy (RUS) spectrum is generated from a spherical object. Sphere parameter values for the spherical object are determined from first components of the RUS spectrum. An asphericity value of the spherical object is determined from second components of the RUS spectrum and the spherical parameter values. The asphericity value is then compared with predetermined values to grade the spherical product.

Jones, U.S. Pat. No. 5,284,058 discloses a method for measuring complex shear or Young's modulus of a polymeric material wherein first and second beams of preselected lengths and different thickness are disposed in parallel spaced relationship firmly held at the ends thereof and first and second spaced gripping members are attached along the beams, a specimen of polymeric material is disposed between confronting surfaces of the gripping members, a time varying force is applied to one beam, the time varying displacements of the beams are measured, and the modulus of the polymeric material is calculated from the measurements.

Tsuboi, U.S. Pat. No. 5,179,860 discloses a defect detecting method which includes the steps of vibrating the object, picking up the vibration, and detecting that a spectrum of the characteristic vibration of the object to be measured is

separated into two portions. The method can also be used to detect cracks by vibrating an object, picking up the vibration, and detecting that an odd order spectrum of the characteristic vibration of the object to be measured is separated into two portions. A non-through defect can be determined in the same way by detecting that an even order spectrum of the characteristic vibration of the object to be measured is separated into two portions.

Tsuboi, U.S. Pat. No. 5,144,838 discloses a defect detecting method which includes the steps of vibrating the object, picking up the vibration, and detecting that a spectrum of the characteristic vibration of the object to be measured is separated into two portions. The method can also be used to detect cracks by vibrating an object, picking up the vibration, and detecting that an odd order spectrum of the characteristic vibration of the object to be measured is separated into two portions. A non-through defect can be determined in the same way by detecting that an even order spectrum of the characteristic vibration of the object to be measured is separated into two portions.

Clark, Jr. et al., U.S. Pat. No. 4,944,185 discloses a method for nondestructively inspecting the integrity of a material by tagging the material, applying the material, activating the tagged particles to cause an inherent structural resonance in the tagged material, monitoring and measuring the structural resonance of the material with a probe, and relating the structure resonance of the material to the structural integrity of the material. The invention has particular application to a material such as an adhesive material.

Slettemoen, U.S. Pat. No. 4,689,993 discloses a method and apparatus for measuring and mapping vibrations wherein one or more local sensors and a measuring means make local registrations and frequency decompositions of the vibrations of an oscillating object. The same sensors and measuring means can also be used with an image-forming unit and an associated measuring means for local and image-forming recording of the vibrations of an oscillating object.

Chamuel, U.S. Pat. No. 4,461,178 discloses a method for ice detection wherein a flexural wave and a compressional wave is propagated through a structure. Ice impacts the propagation speed of the flexural wave, as do others, i.e. temperature, etc. These other factors are taken into account by the use of the compressional wave which provides a baseline for the structure at the particular conditions encountered.

Yost, U.S. Pat. No. 5,736,642 disclose a method of nonlinear ultrasonic scanning to detect material defects wherein first and second frequencies are propogated and combination frequencies result, i.e. a sum wave or a difference wave ($f_1 \pm f_2$).

Additionally, there have been previous efforts at producing methods for detection of ice.

Conventional methods of ice detection utilize various types of energy: cross-polarized coherent light (U.S. Pat. No. 5,650,610) laser beam (U.S. Pat. No. 5,823,474), fiber optic sensors (U.S. Pat. No. 5,748,091), electrical conductivity sensors (U.S. Pat. No. 5,621,400), piezoelectric film sensor (U.S. Pat. No. 5,206,806), and ultrasonic sensors (U.S. Pat. Nos. 4,461,178 and 5,456,114). Ultrasonic sensing devices are based on the principles of linear acoustics. These include effects of reflection, scattering, transmission, absorption of probe acoustic energy. The presence of ice coating leads to phase and/or amplitude variation of received signals while the frequencies of the received signals are the same as of emitted probe signals.

None of these previous efforts, taken either alone or in combination teach or suggest all of the elements, nor all of the benefits and utility of the present invention.

OBJECTS AND SUMMARY OF THE INVENTION

It is a principal object of the present invention to provide a method and apparatus for the non-destructive inspection and evaluation of defects in structures and/or ice on structures.

It is another object of the present invention to provide a method for detecting and locating defects in structures, or ice on structures, on the basis of the modulation response of the structures.

It is an additional object of the present invention to provide a method and apparatus for detecting and locating defects in structures, or ice on structures, by observing the modulation of high frequency ultrasonic signal by low frequency vibration.

It is another object of the present invention is to provide a method and apparatus for detecting and locating defects in structures, or ice on structures, which method and apparatus have high sensitivity and which are applicable to highly non-homogenous structures including composites, engine components, etc.

It is even another object of the present invention to provide a method and apparatus for locating a defect in a structure, or ice on a structure, by varying the relative position between a point of application of the low frequency vibration and a receiver.

It is still another object of the present invention to provide a method and apparatus for locating defects in a structure, or ice on a structure, wherein the low frequency signal provides a localized area of increased excitation which increases the side bands of the received signal when positioned near a defect.

It is still another object of the invention to provide a method and apparatus for localization of defects in structure by transmitting and selecting a sequence of short bursts of the high frequency signal modulated by the low frequency vibration.

The modulation acoustic testing method and apparatus of the present invention employs a high frequency probing signal and a low frequency vibration signal. These signals are applied to a structure for testing the integrity of the structure. If there is a defect, the low frequency signal causes modulation of the high frequency probing signal. This modulation manifests itself as side-band components in the spectrum of the received high frequency signal. This indicates a defect in a structure or ice on the structure.

There are three modes of modulation method: a vibro-modulation (VM) method where a harmonic vibration is applied with a shaker; an impact-modulation (IM) method where impact vibration is applied with an instrumented hammer; or a self-modulation (SM) method using modulations with vibration present in the structure due to environment (turbulence, traffic, etc.) and/or working conditions (engine, pumps, motors, water flow, etc.).

The defects may also be quantitatively analyzed if the frequency of the high frequency signal is swept over a defined frequency range and the amplitudes of the side bands are measured, averaged, and normalized. The resulting number indicates the size of the defect.

The location of the defect can also be determined. This is called localization. The invention includes two localization modes of operation.

In the first localization mode, the low frequency signal is moved relative to the probe signal and the probe signal is triggered immediately after the low frequency signal. The low frequency signal creates an area of localized distortion. As the low frequency signal is moved near to a defect, the amplitude of the side bands of the received signal is increased.

In the second localization mode, a sequence of short burst high frequency signals is radiated and a signal-processing algorithm is employed which selects the sequences reflected from various areas of the structure tested. The presence the modulation in the selected sequence will indicate the presence of a defect in the respective area.

The present invention also relates to the nondestructive detection of ice on solid surfaces such as aircraft wings, road pavements, etc. The interface between the ice and structure, for the purpose of this invention, can be considered a defect. When used in this manner, ultrasonic probing signals and low frequency vibration signals are applied to a structure to detect ice. The low frequency vibration signals could be either generated in the structure by VM or IM or already present in the structure by operations involving the structure (SM).

Additionally, it should be pointed out that a bonded composite structure can be tested by the present invention for detection of defects relating to unbonding and also for assessing the quality of the bondings that are in place.

BRIEF DESCRIPTION OF THE DRAWINGS

Other important objects and features of the invention will be apparent from the following Detailed Description of the Invention taken in connection with the accompanying drawings in which:

FIGS. 1*a* and 1*b* show a defect in contact and out of contact as the stress strain is varied according to the graph of FIG. 1*c*.

FIG. 2*a* shows a rough surface defect and its stress strain relationship is shown in the graph of FIG. 2*b*.

FIGS. 3*a* and 3*b* are graphs of the spectra of a probe signal modulated by an impact vibration in a steel pipe with and without defects.

FIG. 4 is a block diagram of the components of the method and apparatus for acoustic detection of defects of the present invention.

FIGS. 5*a* and 5*b* are graphs of the modulation of the high frequency signal by the low frequency vibration. Rarefaction phase of vibration opens a crack reducing intensity of the passing through high frequency signal.

FIG. 6*a* illustrates selected series of modulated ultrasonic burst samples, and FIG. 6*b* shows the spectrum of the samples of FIG. 6*a*.

FIG. 7 is a block diagram of apparatus for detecting defects in a steel pipe.

FIGS. 8*a*–8*c* illustrate transmitted and received signals in the apparatus of FIG. 7.

FIGS. 9*a*–9*c* illustrate the spectra of the signals of FIGS. 8*a*–8*c*, respectively.

FIG. 10 is a block diagram of apparatus to detect ice on an air plane wing.

FIGS. 11*a*–11*b* are spectral diagrams of signals from an aluminum plate with and without ice.

DETAILED DESCRIPTION OF THE INVENTION

The present invention relates to a method and apparatus for detecting and locating defects in structures. The invention employs modulation of a high frequency probing signal with a low frequency vibration signal. The invention includes three modes of modulation, namely, a vibro-modulation method, an impact-modulation method and a self-modulation method. Defects may be quantitatively analyzed by sweeping the high frequency signal over a defined frequency range and examining the amplitudes of side bands that are measured, averaged and normalized. The present invention also relates to the localization of defects and includes two localization modes of operation, namely, a first localization mode wherein the low frequency signal is moved about the structure relative to the probe signal, and a second localization mode wherein sequence of short burst high frequency signals are radiated and a signal-processing algorithm is employed to select sequences reflected from various areas of the tested structure to indicate the location of a defect.

As a brief background, contact-type defects include cracks, unbonds, delaminations, etc. The presence of ice on a structure can be considered, for the purpose of the present invention, a defect. The physical nature of the defect-related modulation is illustrated in FIGS. 1*a* and 1*b*, where a defect is modeled as a contact between two flat solid surfaces. If dynamic (acoustic) stress is applied to this defect, there is no contact at all (full opening) during the elongation phase of the stress, and full contact (closure) during the compression phase. The elastic deformation of medium containing such a defect will be different for elongation and compression leading to a piecewise-linear (nonlinear) stress-strain relationship, as shown in FIG. 1*c*.

A more realistic model of a defect is a contact between two rough elastic surfaces as shown in FIGS. 2*a* and 2*b*. The applied stress will vary the contact area within the defect, leading to a nonlinear elastic deformation.

The stress-strain dependence of a medium containing such contact-type defects will also be nonlinear and can be written in the form of the Taylor's expansion with respect to strain. For simplicity, this relationship can be written for one-dimensional longitudinal deformations:

$$\sigma=E(\epsilon+\beta\epsilon^2+\gamma\epsilon^3+\ldots), \tag{1}$$

where σ is the stress, ϵ is the strain, E is the modulus of elasticity, β, γ, . . . are the nonlinear parameters, which characterize the nonlinearity of the medium. For the small strains used in acoustic NDT, the cubic and higher terms in this expansion can be neglected and the equation (1) retains only linear and quadratic terms of ϵ. This is the case of so called quadratic nonlinearity. Typical values of the nonlinear parameter β as a rule do not exceed 10 for homogeneous media without any defects, so the contribution of the nonlinear quadratic term into the relationship (1) is very small (for small strains) and the media exhibit quasi-linear behavior. The defects may increase the parameter β up to two to three orders of magnitude. Even though the value of the nonlinear term may still be small compared with the linear term ($\beta\epsilon<<1$), its contribution and, consequently, acoustic manifestations are much more visible.

There are various nonlinear acoustic manifestations of the contact-type nonlinearity. One of them is the modulation of a probe ultrasonic wave by lower frequency vibration. In this case, vibration varies the contact area (or alters defect opening) modulating the phase and the amplitude of the higher frequency probe wave.

When dynamic low frequency stress (vibration) is applied to the crack, the crack opens in the phase of elongation and closes in the phase of compression, as shown in FIG. 1. If the probe high frequency wave is passing through, its intensity will diminish on the elongation phase of the low frequency stress (crack is opened) as is shown in the FIG. 5, leading to amplitude to modulation of the probing signal by low frequency vibration. In the spectral domain such a modulation manifests itself as sideband components with respect to the carrier ultrasonic signal frequency peak. Obviously, the level of modulation is proportional to the size of the crack, since the larger the crack, the more pronounced the effect of modulation.

This modulation effect can be observed for various types of defects. FIGS. **3***a* and **3***b* show the spectra of a probe signal modulated by an impact vibration observed in a steel pipe with and without defects. This modulation method has high sensitivity and geometric indifference, and can be used for the non-destructive testing of pipes, welded pipes, valves, airplane wings, etc., as well as for structures or equipment which have an intrinsic vibration including operational machinery (pumps, steam, generators, turbines, etc.) water or gas pressure fluctuations, etc.

Referring to FIG. 4, one representation of the apparatus of the present invention, generally indicated at **10**, is depicted. The device includes an impact hammer **20** or other means for creating a low frequency vibration system in the structure **8** to be tested. Alternate means of creating a low frequency vibration signal can be used as is known in the art.

Additionally, a high frequency probe signal is applied to the tested structure **10** by means of an ultrasonic transmitter **30** or other means known in the art. The probing signal is created by a pulse generator **32** which sends a signal to a gating device **34**. A signal generator **36** also sends a signal to the gating device which gates the signals and sends its output to power amplifier **38** which delivers the signal to the ultrasonic transmitter **30**. The apparatus configuration can, of course, be varied in accordance with what is known in the art.

The hammer **20** includes a sensor which generates a signal for synchronization of system, including the computer means **40** and the pulse generator **32**. A receiver **50** is positionable on the tested structure to receive the modulated signal. An array of receivers **50** can be utilized. The receiver **50** picks up and sends the modulated signal to the computer means **40** for analysis.

Due to the presence of defects, the low frequency vibration modulates the high frequency probe signal. This modulation manifests itself as a side band component in the spectra of received signal. Recent examples of the applications of these methods include detection of: unbonding of titanium plates used for airspace applications; cracks in Boeing 767 steel fuse pins; cracks in combustion engine cylinder heads; cracks in a weld in a steel pipe at a nuclear power station; adhesion flaws in bonded composite structures; cracks and corrosion in reinforced concrete; and cracks in rocks. There is strong correlation between presence of contact-type defects such as cracks, debondings, delaminations and measured sideband spectral components. In some experiments the level of the sideband components (in presence of a defect) exceeded the reference signal (without defect) by over 30 dB. These tests demonstrate capability of the modulation methods to detect flaws in highly non-homogeneous structures where conventional acoustic methods are not applicable. Among such structures are composite materials, airframes and engine components, civil structures, etc.

The present invention can be used in another mode to determine the location of the defect. In the first localization mode, the low frequency signal is moved relative to the probe signal and the probe signal is triggered immediately after the low frequency signal. The low frequency signal creates an area of localized distortion. As the low frequency signal is moved near to a defect, the amplitude of the side bands of the received signal is increased.

In the second localization mode, a sequence of short burst high frequency signals is radiated and a signal-processing algorithm is employed which selects the sequences reflected from various areas of the structure tested. The presence of the modulation in the selected sequence will indicate the presence of a defect in the respective area.

More particularly, the first localization mode involves varying the relative distance between the probing signal, the low frequency signal and the receiver, such as by moving the low frequency signal around the tested structure and analyzing the signal. Upon an impact by an impact hammer, a localized area of increased excitation around the area of impact is formed, which thereafter becomes a waveform. It is the waveform that is used to modulate the high frequency probing signal in the testing mode. However, the localized impact distortion is relied upon in the localization mode. The computer acquires a probe signal that has been delayed from impact to exclude the vibration caused by the localized stress of the impact hammer. The probe signal is acquired immediately after impact to correspond to the short lived localized vibration of the impact hammer. By utilizing the localized vibration, the amplitude of the sidebands of the received signals is increased when the impact hammer is located near a defect. An impact produced vibration field can be represented by two parts: near field stress (localized in the vicinity of the impact) and propagating wave stress. As a rule, near field stress is much greater than propagating wave stress. The propagating wave field may cover the entire structure; this leads to modulation of the ultrasonic probing signal in the presence of a defect. This modulation serves as an indication of the defect. With this, the closer the impact to the defect, the greater the near field stresses applied to it, leading to a higher modulation level. Therefore, impacting at different locations and correlating the impact location and level of the modulation allows for locating defects.

In the second localization mode, localization of a defect is achieved by varying the parameters of applied ultrasonic and vibration inputs. Higher frequency ultrasonic waves may irradiate a smaller part of the tested structure, so the inspected area can be reduced accordingly. In addition, the location of a defect can be determined by varying the location of the applied impact. A new algorithm using periodic burst ultrasonic signals has been developed. Sequences of the burst ultrasonic signals are transmitted. Each burst has a carrier frequency fc. The duration between the burst is determined by the repetition frequency Fr.

The algorithm selects and processes only those bursts which travel/reflect within/from the area of interest. The duration of each burst is sufficiently short to be resolved from the signal reflected from the other parts of the structure. The repetition frequency, Fr, is chosen to satisfy the following condition: Fr>2Fv, where Fv is the frequency of the modulation vibration. This is equivalent to the Nyquist frequency condition, since the selected pulses will be used to "sample" the modulation envelope, as illustrated in FIGS. **6***a* and **6***b*.

The algorithm has been tested using a steel pipe **60** with welded flanges as shown in FIG. 7. One of the flanges has a defect (a crack). The opposite flange is free of defects. The